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Statistical Estimation of Reliability Values for Large-Panel Buildings Based on Passportization Results

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Abstract

In 2017-2018 and 2023-2024, a full passportization of the housing stock of apartment buildings in the city of Almaty (Republic of Kazakhstan) was carried out for the first time. The database includes 2666 multi-story large-panel buildings of different numbers of stories, from 2 to 9 floors. The aim of this study is to assess the reliability of standard-series large-panel buildings based on previous experimental research and passportization results, as well as to evaluate their seismic resistance and reliability using passportization data. The latest earthquakes in Almaty have allowed for refinements in seismic impact models. Therefore, the reliability assessment has been conducted considering this information using the Monte Carlo method. The technical condition of large-panel buildings has been assessed. The earthquake recurrence is taken into account according to the current "Map of seismic zoning of the Republic of Kazakhstan". Reliability value for the whole group of large-panel buildings has been obtained. It is revealed that large-panel buildings with the first flexible or brick floor are not earthquake-resistant. For the first time, the theoretical analysis of reliability and failure values for 2 types of large-panel buildings with the use of experimental data is performed. Regional peculiarities of seismic impact for Almaty City are taken into account. The results of reliability and failure values estimations are used for practical recommendations on risk reduction and expected losses in case of possible earthquakes. The novelty lies in the reliability and failure assessment based on the large-scale passportization of the housing stock in Almaty. It is established that the main types of large-panel buildings are earthquake-resistant. Estimates of earthquake resistance according to the results of passportization and the results of reliability calculations coincided. It is proposed to reinforce large-panel buildings with the first flexible or brick floor (33 buildings). The method of reinforcement should be determined by special studies.

Keywords: Passportization; Risk; Large-Panel Building; Flexible Floor; Reliability; Repeatability; Failure.

1. Introduction

The metropolitan area of Almaty is the most highly seismic area in Central Asia. More than 2 million people live in the city. Seismicity of the city is caused by seismogenic zones of the Northern Tian Shan. For the last 140 years, 3 strong earthquakes with magnitudes of 7-8 have occurred here: the Vernen earthquake of 1887, the Chilik earthquake of 1889, and the Kebin (Kemin) earthquake of 1911. Under these conditions, the seismic safety of the population should be ensured. It should be noted that earthquakes with a magnitude above 8 have occurred. At such magnitudes, earthquake intensities of up to 10 on the seismic scale can be expected. The review study by Wardach & Krentowski [1] considers the studies of large-panel buildings conducted since the beginning of the XXI century. In Eastern European countries, large-panel buildings constitute a significant portion of the housing stock. However, most of these buildings were constructed in the 1970s, and their service life is now coming to an end. Approaches to calculating their seismic resistance have evolved, necessitating further analysis regarding the extension of their operational lifespan.

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This article reviews key research directions on large-panel buildings and highlights the need for developing experimental methods for their assessment. One advantage of this construction method is the ability to manufacture panels in housing construction factories, significantly accelerating the building process. As a result, large-panel buildings represent a substantial share of the housing stock in Eastern Europe and the former Soviet Union. However, further research is required, particularly regarding the durability of these buildings in seismically active regions.

The first large-panel buildings were constructed in the 1950s and have now been in use for 50–60 years. Therefore, assessing their technical condition, particularly the quality of joint connections, remains a pressing issue. Wardach [2] examines changes in the stiffness characteristics of panel joints. It is noted that both destructive and non-destructive testing methods are used in joint connection assessments. Experimental research plays a crucial role in developing accurate mathematical models for evaluating the strength and deformation capacity of these joints. Various types of defects in the walls of large-panel buildings are studied in Wardach et al. [3]. It is well known that after many years of operation, cracks begin to appear on the walls of large-panel buildings. This is a serious issue for residents, as it significantly affects their sense of security. Different types of cracks and their possible causes are analyzed. Szulc & Piekarczuk [4] presents the results of an inspection of over 400 large-panel buildings constructed in Poland. The study includes laboratory and field test results, which have been used to develop diagnostic methods for assessing the technical condition of large-panel buildings.

A new technical solution for joint connections in large-panel buildings is proposed in Yudina et al. [5]. This solution is achieved through the development of new types of prefabricated element connections with a high degree of factory readiness. All panels in large-panel buildings are joined using anchor-bolt connections or non-welded inter-panel joints in the form of cable loops. The elimination of welding enhances the reliability of the joint connections.

Due to their high level of industrialization, large-panel buildings have become widespread in seismic regions. Studies [6–8] indicate that in such buildings, both external and internal walls bear all vertical and horizontal loads acting on the structure. Buildings between four and twelve stories high demonstrated good seismic resistance during major earthquakes, such as the Dzhambul in 1971, Dagestan in 1975, Carpathian in 1977, and Spitak in 1988 earthquakes. Experimental studies on large-panel buildings are provided in Zhunusov et al. [9] and Zhunusov et al. [10], while wall tests are detailed in Shakhnovich & Azhibekov [11]. Based on the analysis of strong earthquake impacts, quantitative assessments of damage have been conducted in Tsipenyuk [12, 13].

Denisov [14] analyzes instrumental recordings from an engineering seismometric station installed on a large-panel building during a five-magnitude earthquake. This is one of the first instrumental recordings of an earthquake on such buildings. The results of the first large-scale inspection of large-panel buildings in the Republic of Kazakhstan following the Dzhambul earthquake on May 10, 1971, are presented in Zhunusov et al. [15]. Cherepinsky [16] and Cherepinsky et al. [17] look at the findings from a study that tested how a large-panel building behaves on special foundations designed to reduce earthquake effects. It is noted that the use of such seismic isolation foundations in the design of panel buildings for seismically hazardous areas could reduce costs associated with anti-seismic measures.

In Almaty city, the first large-panel houses for construction in conditions of 9-point seismicity were designed by the institute "Kazgorstroyproekt" and in 1959-1960, 2 such houses were built. In 1961-1962 the same institute developed a standard series of four-story large-panel residential buildings, I-464 AS. In the works of the KazpromstroyRIproekt Institute, the study of seismic resistance of large-panel buildings was comprehensively conducted using various methodologies as of the late 1980s. However, modern probabilistic methods for assessing building seismic resistance have not yet been applied.

In the mid-1990s, the first building certification in the central part of Almaty was carried out with the participation of Japanese specialists. However, since large-panel buildings were relatively scarce in this area, quantitative assessments of building damage were not obtained. During 2017–2018, a comprehensive certification of the multi-apartment residential stock in Almaty was conducted [16–23], resulting in the creation of electronic passports for the inspected buildings [18, 19]. Lapin & Yerzhanov [20] and Aldakhov [21] proposed a method for assessing reliability and seismic risk values within a settlement, considering the new seismic zoning map of the Republic of Kazakhstan.

The initial assessments of seismic risk were qualitative in nature [22, 23]. To fully describe reliability as the probability of failure-free operation and seismic risk, it was necessary to link the degree of building damage with its reliability values [24–26]. The development of a seismic risk assessment method using energy-based seismic resistance criteria [27] and seismic risk models aimed at reducing earthquake-related losses in settlements [28, 29] has advanced.

A rigorous approach to determining reliability and risk values was proposed in the monograph [30], utilizing results from engineering seismology and experimental data on the behavior of various building types, including large-panel buildings. The monograph provides numerous examples of determining building reliability as the probability of failure-free operation.

The results of the 2017–2018 certification in Almaty are analyzed by Rashid et al. [31]. Reliability and risk assessments were conducted for various building types, including large-panel, frame, and monolithic structures. However, all results were based on building damage data classified according to the EMS scale. Since this seismic scale is not officially used in the Republic of Kazakhstan, these reliability and risk assessments may not be applicable to Kazakhstan. Instead, Kazakhstan follows the MSK-64(K) seismic intensity scale.

Methods for assessing the reliability of shear wall structures are presented in Kim & Wallace [32]. The walls of large-panel buildings primarily function under shear forces. Both analytical methods based on exact solutions and numerical methods using the Monte Carlo approach are applied. Random variables are assumed to follow either a lognormal or normal distribution. In the statistical modeling process using the Monte Carlo method, 1000 realizations were generated. For seismic impact scenarios, further studies within nonlinear dynamic models are recommended. Various probabilistic methods for determining the reliability of buildings and their elements using Eurocode models are analyzed in Costa & Beck [33] and Xu et al. [34]. Different approaches to modeling dynamic loads are proposed. It is noted that determining the probability distribution of the maximum values of the sum of two or more random processes presents a significant challenge. The obtained results can be applied to describe random seismic loads.

In the study of building reliability by Shao et al. [35], significant attention is recommended for investigating the soil conditions at construction sites. For computational building models, the Pasternak two-parameter model is suggested to describe soil conditions. However, the complexity lies in defining the statistical characteristics of the Pasternak model parameters. For certain soil types, these statistical characteristics may not be entirely reliable. The findings of the study by Fadel Miguel et al. [36] appear significant. Between 2010 and 2015, Chile experienced three earthquakes with magnitudes of 8 or higher. Under such conditions, the use of various types of seismic isolation systems is necessary to reduce seismic loads. To decrease these loads and, consequently, lower the probability of building failure, nonlinear pendulum tuned mass dampers (PTMD) are proposed. The problem of optimizing the damper parameters within the framework of a mathematical building model based on failure probability is addressed in Ontiveros-Pérez & Miguel [37]. This approach ensures a reduction in seismic loads under high acceleration conditions at the building's foundation. Additionally, for seismic isolation in cases of highly intense seismic events, a kinematic-type system developed in the Republic of Kazakhstan can be utilized [38].

The issue of building reliability is closely related to the assessment of economic damage (or financial losses) caused by natural disasters such as earthquakes and floods. Damage is strongly linked to the concepts of reliability, risk, and failure probability, and should have a probabilistic quantitative relationship with them. Forecasting damage under seismic impact is a critical task that requires probabilistic characteristics. However, there is no universal approach for estimating damage in emergency situations. In this context, Thiel et al. [39] is of particular interest. It presents a complex method for assessing uncertainty, which can be applied to manage technical risks. The study even considers the reliability of damage estimations, which is crucial for decision-making.

It is also worth noting that for determining building reliability, an economical approach to modeling seismic impact as a random process is highly important. Such a method is proposed in Lapin et al. [40]. It is based on a non-canonical spectral representation of the random process and demonstrates high computational efficiency. Some studies on seismic risk assessment are based on evaluating the probability of structural failure. In Liu & Wang [41], building parameters are considered as random variables described by multivariate lognormal distributions. The Monte Carlo method is used to determine the probability of structural failure, allowing for the consideration of nonlinear behavior in real structures.

In Fathi-Fazl et al. [42], the risks of structural failures in low-seismicity areas of Canada are analyzed. The obtained results may be applicable to similar regions in the Republic of Kazakhstan and other countries. An example of risk assessment for old buildings constructed before 1990 is provided in Bunea et al. [43]. This study examines buildings designed according to various construction standards that have been subjected to earthquakes in the Vrancea region (Romania). The proposed methodologies may be useful for assessing failure probabilities and risks for existing buildings.

The review highlights the existence of numerous methods for assessing structural failures and the probability of failure-free operation of buildings of various types. However, relatively few studies focus on large-panel buildings. This is due to their historically strong reputation for seismic resistance. However, recent earthquakes in Turkey have shown that very few buildings can withstand severe, high-magnitude earthquakes. Therefore, assessing the reliability, risk, and seismic resistance of such buildings based on the passportization of over 2000 structures is highly relevant—especially considering that earthquakes with magnitudes above 8 are possible in Almaty.

Below, reliability and risk assessments of such buildings are carried out using the results of passportization. Quantitative data on failure and reliability assessments of large-panel buildings for the city of Almaty are obtained for the first time.

Thus, the following objectives are addressed:

- According to the results of passportization, identify the number of earthquake-resistant and non-earthquake-resistant large-panel buildings;
- Analyze their design solutions;
- Selectively assess the technical condition of buildings and provide a qualitative assessment of earthquake resistance.
- Estimate the reliability value (probability of failure-free operation) for a group of large-panel buildings;
- On the basis of the specified models of seismic impact for Almaty city and application of experimental results of vibrodynamic tests to carry out theoretical assessment of reliability (probability of failure-free operation) of such buildings.
- Compare the obtained results with the analysis of earthquake consequences and the findings of other authors.

Draw conclusions about policies for strengthening non-seismic resistant buildings, including the possible use of seismic isolation systems.

2. Methods and Objects

2.1. Large-Panel Apartment Buildings

Mass construction of large-panel buildings in Almaty was started in 1959 and continued until 1992.

The maximum volumes of erection of large-panel buildings were reached in 1985-1988. During this period of time, the volume of large-panel buildings commissioned annually approached 400 thousand m^2, which amounted to about 70% of the total volume of housing construction in Almaty.

To date, the total area of large-panel buildings erected in Almaty and adjacent territories is 9.7 million square meters. Approximately 600 thousand people live in large-panel buildings.

The following series of large-panel buildings were mainly used in the construction of Almaty: 1-464-AS; 1KZ-464-DS; 69; E-147; 158.

Buildings of the 464 series were designed for the construction of 4-5-story residential buildings, the 69 series for 5-story buildings, the E-147 series for 8-story buildings, and the 158 series for 9-story buildings.

The structural solutions of the buildings of all the mentioned series were based on cross-wall structural schemes formed by longitudinal and transverse load-bearing walls united for joint operation by vertical butt joints and inter-floor slabs mounted from continuous room-sized slabs. Four-story and five-story buildings had one interior longitudinal wall, while eight- and nine-story buildings had two.

Initially, only four-story buildings of the 1-464-AS series were erected in the city. The transverse wall spacing in these buildings was 2.6 and 3.2 meters. The outer walls were assembled of three-layer panels of room size. The thickness of the exterior panels was 250 mm, including the thickness of the load-bearing layer - 100 mm. The internal walls were assembled from panels per room or two rooms. The thickness of reinforced concrete panels of internal walls was 120 mm. Connections between the panels were made by welding of embedded parts.

Since 1967, the construction of buildings of the 1-464-AS series was stopped, and large-panel buildings of the 1KZ-464-DS series started to be constructed in Almaty. Buildings of this series are a modification of buildings of the 1-464-AS series. The most significant constructive differences between these series were reduced to the differences in the design of vertical joints between the wall panels.

In the buildings of the 1KZ-464-DS series, the exterior wall panels had keyed recesses and reinforcing bars on the side edges. Due to the presence of recesses between adjacent panels in the plan of the building, the so-called "vertical wells" are formed, in which vertical reinforcing bars are placed through the entire height of the building. Vertical wells, after welding horizontal reinforcing bars from the panels, are sealed with concrete. The construction of buildings of the 1-464-DS series continued until 1992.

The buildings of series 69, E-147, and 158 can be referred to as large-panel buildings of the next generation. The comfort of these buildings, determined by the quality of planning solutions as well as the soundproofing and thermal properties of wall constructions, significantly exceeded that of the 464 series buildings.

The transverse wall spacing in the buildings of this series was increased to 3.6 m. The thickness of the interior wall and floor panels became 160 mm, and the thickness of the exterior wall panels became 350 mm.

The butt joints between panels have also undergone significant changes. In buildings of series 69, E-147, and 158, all vertical joints between wall panels are made by welding of reinforcing bars, followed by caulking of vertical wells, and horizontal joints between panels and joints between floor slab panels are made in the form of reinforced concrete keys.

Large-panel buildings with "first flexible floors" should be referred to as a special class of large-panel buildings. Buildings of modern construction with the first flexible floors belong to the class of seismically hazardous objects, the destruction of which under seismic impact of design intensity will be accompanied by catastrophic consequences - collapse of buildings as a whole. Figure 1 shows the location of the city of Almaty.

Figure 1. The city of Almaty and the Republic of Kazakhstan (https://www.shutterstock.com/ru/image-vector/kazakhstan-map-capital-astana-most-important-242869400)

2.2. Buildings with Seismic Systems

In Almaty, there is a significant number of large-panel buildings with different seismic isolation systems [11, 12, 31]:

- 5-story building of series 69 on kinematic foundations (KF);
- 5 and 9-story houses of series 158 on (KF);
- 2-story building of series 226 on a site with a seismicity of 10 at (KF);
- 9-story building of series 158 on fluoroplastic gaskets (FG).

Revealed:

- Elastic-nonlinear character of the foundation deformation diagram in the “force-displacement” axes;
- Increased dissipative capacity noted from the free vibration decrement of the seismically insulated building.
- Conclusions were drawn from the test results:
- Large-panel buildings on kinematic foundations under intensive dynamic and seismic effects operate as single-mass elastic-nonlinear systems;
- No cracks were observed in wall panels and floor slabs during vibration tests;
- The design scheme of a seismically insulated building is well described by a single-mass nonlinear system due to small deformations of the basement part of the house;
- Seismic forces are reduced by a factor of 2 or more, depending on the prevailing period of seismic impact;
- Economic effect from the application of KF is achieved by increasing the number of stories of buildings or using standard series designed for lower seismicity.
- Application of seismic isolation systems allows to reduce up to 2 times the calculated seismic loads, to reduce by 5-7% the steel consumption and by 3-5% the estimated cost of the building.

3. Results

3.1. Technical Condition of Large-Panel Houses

During passportization, 8 large-panel residential buildings were surveyed, including: in Auezov district - 1 house of 1Kz-464AS series; in Bostandyk district - 4 houses of 1Kz-464DS series; in Medeu district - 3 houses of 1Kz-464DS series. Buildings of 1Kz-464AS series were designed for the construction of 4-story residential buildings; buildings of 1Kz-464DS series were designed for the construction of 5-story residential buildings. The structural solutions of large-panel buildings of the above series are based on cross-wall structural schemes formed by longitudinal and transverse load-bearing walls united for joint operation by vertical butt joints and interstory floor slabs mounted from continuous room-sized slabs. Four-story and five-story buildings have one interior longitudinal wall.

Initially, only four-story buildings of 1-464-AS series were erected in the city. The transverse wall spacing in these buildings was 2.6 and 3.2 meters. The outer walls were assembled of three-layer panels of room size. The thickness of the exterior panels was 250 mm, including the thickness of the load-bearing layer - 100 mm. The internal walls were assembled from panels per room or two rooms. The thickness of reinforced concrete panels of internal walls was 120 mm. Connections between the panels were made by welding of embedded parts.

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The first serious test of earthquake resistance of large-panel buildings was carried out in 1967 in Almaty, during the construction of a mudflow protection dam in the Medeu tract. The results of seismic blast tests in Medeu for the first time clearly demonstrated high resistance of large-panel buildings to intensive (8-9 points) dynamic impacts. The effectiveness of the developed anti-seismic measures has been repeatedly confirmed by the consequences of strong earthquakes. The most obvious proof of the high reliability of large-panel buildings should be considered the fact that even during such destructive earthquakes as the Kairakkum in 1986 and the Spitak in 1988, there were no fatalities or significant injuries among the occupants of large-panel buildings, and the buildings themselves were quite suitable for further operation.

Analysis of the condition of large-panel buildings subjected to seismic impacts indicates that such buildings have significant reserves of strength in relation to design loads and the ability to develop significant plastic deformations. At the same time, structural solutions and the condition of joints between panels play an important role in ensuring the safety of large-panel buildings under seismic impacts.

The problems of the condition of butt joints between panels are the most urgent for large-panel buildings of the 1-464-AS series.

3.1.1. Qualitative Assessment of Seismic Vulnerability of Large-Panel Residential Buildings of 1-464-AS Series

Large-panel housing construction in Almaty began in 1959 with the construction of residential buildings of the 1-464-AS series, the so-called "Khrushchevka". Their construction continued until 1967. The service life of large-panel buildings of the 1-464-AS series today is 58-66 years; the planning solutions of these buildings do not meet modern architectural standards.

Connections between the panels are made by welding of embedded parts, without caulking the joints of wall panels, which does not meet the requirements of the current norms. In other words, these buildings can be considered obsolete.

Previously performed by specialists of the institute JSC "KazRDICA", a detailed inspection of the buildings of the 1-464-AS series, erected in 1960, showed that at least 30% of the joints between the panels of internal walls enclosing stairwells and adjacent to bathrooms and kitchens are subject to corrosion. The residual thickness of the steel elements located in these areas is no more than 60% of the original thickness of the embedded parts. All other joints located between the panels away from the rooms with wet processes are in satisfactory condition.

Significant corrosion of part of the butt joints between the interior wall panels is an undoubted hazard for large-panel buildings of the 1-464-AS series.

In large-panel residential buildings of the 1-464-AS series, it is prohibited to install and/or enlarge openings in wall and floor panels.

Large-panel residential buildings of the 1-464-AS series by volume-planning solutions meet the requirements of SP RK 2.03-30-2017* and, with satisfactory quality of construction work and the absence of unauthorized alterations associated with the device and/or expansion of openings in the panels of walls and floors, can be considered as earthquake-resistant.

At design earthquakes of 9 MSK in large-panel residential buildings of the 1-464-AS series, with satisfactory quality of construction works and absence of alterations affecting load-bearing structures, damage on the descriptive scale MSK-64 K from 1 (insignificant damage) to 2 (moderate damage) degrees is possible. According to cl. 4.16 of SP RK 1.04-110-2017, large-panel residential buildings of the 1-464-AS series with such damages can be assessed as serviceable, requiring current repair.

Taking into account that the service life of the buildings of the 1-464-AS series has expired, to ensure the safety of the people living in these buildings, it is necessary to carry out a detailed inspection of these buildings and develop projects for reinforcing the damaged joints.

3.1.2. Qualitative Assessment of Seismic Vulnerability of Large-Panel Residential Buildings of 1-464-DS Series

Large-panel apartment buildings of the 1-464-DS series were built in Almaty from 1967 to 1992. The butt joints between the panels of external walls were caulked. The service life of the buildings of the 1-464-DS series is 33-58 years; the planning solutions of these buildings do not meet modern architectural standards. The degree of seismic resistance of these buildings is higher compared to the buildings of the 1-464-AS series. In large-panel residential buildings of the 1-464-DS series, it is prohibited to install and/or enlarge openings in wall and floor panels. Large-panel residential buildings of the 1-464-DS series on volume planning and structural solutions meet the requirements of SP RK 2.03-30-2017* and, with satisfactory quality of construction work and the absence of unauthorized alterations associated with the device and/or expansion of openings in the panels of walls and floors, can be considered as earthquake-resistant.

At design earthquakes of 9 MSK in large-panel residential buildings of the 1-464-DS series, with satisfactory quality of construction works and absence of alterations affecting load-bearing structures, damage on the descriptive scale MSK-64 K from 1 (minor damage) to 2 (moderate damage) degrees is possible. According to cl. 4.16 of SP RK 1.04-110-2017, large-panel residential buildings of the 1-464-DS series with such damages can be assessed as serviceable, requiring current repair.

3.2. Results of Passportization

Table 1 shows the results of passportization by series of large-panel buildings. Large-panel buildings with the first flexible or brick floor are not earthquake-resistant here. This is 1.24 % of the total number of large-panel buildings. Therefore, the group of large-panel buildings in general meets the norms of earthquake-resistant construction and seems to be safe enough for living. The group of large-panel buildings is the most numerous in the city of Almaty.

Table 1. Large-panel apartment buildings by series

№	Series of large-panel buildings	Quantity buildings	Earthquake resistant buildings	Not earthquake resistant buildings
1	464-DS	1292	1292	-
2	464-AS	500	500	-
3	69	143	143	-
4	E147	28	28	-
5	158	663	663	-
6	Other types of efficiency	40	7	33
	Total	**2666**	**2633**	**33**
	1 shedding		2 shedding	

Assuming the reliability criterion to be the fact of attributing the building to the set of earthquake-resistant houses, we obtain the value of the probability of failure-free operation (reliability).

$$W = 1 - (33/2666) = 0{,}9876 \tag{1}$$

Estimate 1 is an integral assessment of reliability of a group of large-panel buildings without taking into account earthquake recurrence, which is convenient to use for comparison of reliability assessment of different structural types - large-panel, brick, frame, etc.

Figures 2 to 4 show earthquake-resistant houses and Figures 5-9 earthquake-resistant large-panel houses.

Figure 2. Auezov Str., building 65 (earthquake-prone house)

Figure 3. Orbita-2 m/dist., building 2 (earthquake-prone building)

Figure 4. Orbita-2 m/dist., building 6 (earthquake-prone building)

Figure 5. Mamyr-1 m/dist., building 9 (earthquake-resistant house)

Figure 6. Mamyr-2 m/dist., building 15 (earthquake-resistant house)

Figure 7. Tastak-1 m/dist., building 6 (earthquake-resistant house)

Figure 8. Tastak-1 m/dist., building 11 (earthquake-resistant house)

Figure 9. Tastak-1 m/dist., building 13 (earthquake-resistant house)

3.3. Experimental Studies of Earthquake Resistance of Large-Panel Buildings

The first serious test of earthquake resistance of large-panel buildings was carried out in 1967 in Almaty, during the construction of the mudflow dam in the Medeu tract. The construction of the mudflow protection dam was carried out by means of powerful explosions, during which ground shaking in the area within a radius of up to 2 km from the place of explosions was estimated at 7-8 points on the MSK-64 scale [16].

The research complex was carried out at a site located at a distance of 800 m from the explosion site. Six full-scale fragments of buildings of various structural schemes, including large-panel, brick and frame buildings, were erected on this site. All buildings were designed in accordance with the requirements of the existing norms, based on the conditions of construction in areas with seismicity of 9 points. During the explosion (total explosive weight was 3900 tons), the maximum horizontal accelerations at the level of the top of the building foundations reached 0.4-0.6g, and the accelerations at the level of the brick and large-panel building coverings reached 0.9g and 0.6g, respectively. Inspection of the buildings showed that the brick building was heavily damaged after the seismic blast, while the large-panel building was slightly damaged. The results of seismic-explosion tests in Medeu for the first time clearly demonstrated high resistance of large-panel buildings to intensive dynamic impacts and allowed us to objectively compare the seismic resistance of large-panel and brick buildings.

To date, large-panel buildings can be considered the most experimentally investigated structural systems. Over the last 30 years, only the institutes CRIEHD (Central Research Institute of Experimental Housing Design) and KazRDICA have conducted dynamic tests of about 50 full-scale large-panel buildings [6, 7, 12, 13]. About 20 more full-scale buildings were tested by specialists of V.A. Kucherenko CSRIBS (Central Scientific Research Institute of Building Structures), TbilZSRIED (Tbilisi Zonal Scientific Research Institute of Experimental Design), ArmRICA, TashZSRIED, and others. Many of the experimental objects were subjected to dynamic impacts 2-3 times higher than the design seismic loads, and some were brought to the limit state.

It is worth noting the testing of two large-panel buildings of the I-464 DS series in Navoi city in 1978 [16, 17]. One building was erected on conventional strip foundations, the other on seismic-isolating kinematic foundations. The dynamic impact was created by a vibrating machine of inertial action B3. The building on kinematic foundations was not damaged. The building on strip foundations received damage of approximately the third degree. The results of the tests should be recognized as successful, as the damage to the building on strip foundations did not threaten the occupants, and the tests of the house on KF showed the effectiveness of the seismic isolation system.

Numerous dynamic tests of large-panel buildings have shown that shear deformations predominate in buildings 5 to 9 stories high. The effectiveness of the developed anti-seismic measures has been repeatedly confirmed by the consequences of strong earthquakes. The most obvious proof of the high reliability of large-panel buildings should be considered the fact that even during such destructive earthquakes as the Kairakkum (1986) and Spitak (1988) earthquakes, there were no fatalities or significant injuries among the occupants of large-panel buildings, and the buildings themselves were quite suitable for further operation. Analysis of the condition of large-panel buildings subjected to seismic impacts indicates that such buildings have significant reserves of strength in relation to design loads and the ability to develop significant plastic deformations. At the same time, structural solutions and the condition of joints between panels play an important role in ensuring the safety of large-panel buildings under seismic impacts.

The problems of the condition of the butt joints between the panels are the most urgent for large-panel buildings of the 1-464-AS series, installed more than 30-40 years ago. In 1978 and 1990, within the complex of research works connected with the estimation of earthquake resistance of buildings of existing construction and studying the possibility of modernization of some of them, the specialists of KazRDICA JSC carried out a detailed survey of two large-panel buildings of the 1-464-AS series, erected in 1960.

The results of the inspection of the buildings of the 1-464-AS series showed that more than 30% of the joints between the panels of the internal walls enclosing the stairwells and adjacent to the bathrooms and kitchens are subject to corrosion. The residual thickness of the steel elements located in these areas is no more than 60% of the original thickness. All other butt joints located between the panels removed from the rooms with wet processes are in satisfactory condition.

3.4. Calculation on Real Accelerograms of the 69 Series Building

Let's perform calculation of a 5-story large-panel building of 69 series on real accelerograms. The building was tested with the vibration machine B3 [10]. The building behaved as a weakly nonlinear dynamic system. Therefore, when calculating for real accelerograms, the dynamic model can be assumed as a single-mass linear system

$$\ddot{x} + 2\frac{\delta}{T}\dot{x} + \left(\frac{2\pi}{T}\right)^2 x = -\ddot{x}_0 \tag{2}$$

The coefficients of Equation 2 are taken from experimental data. Logarithmic decrement of oscillations δ=0.21, experimental period of oscillation T=0.28 sec.

Seismicity of the territory of Almaty city and its surroundings is connected with the activity of the Almaty and Kemin tectonic faults. Three seismogenic zones are the most dangerous for the territory of the city - Almaty, Zailiysk and Chilik-Kemin. Their seismic potential is very high - earthquakes with centers in these zones and magnitudes up to 8.5 are possible. Extension of zones is connected with extension of Zailiysk and Kungei Alatau ridges. In the past there were the strongest earthquakes - Vernen and 1887 with magnitude 7.2 and Kemin 1911 with magnitude 8.2 (according to some data its magnitude was 7.9).

The sample contains accelerograms of earthquakes with magnitudes 6.3-7.4 and hypocentral distances from the earthquake origin from 19 to 89 km. Accelerograms of earthquakes should be used without normalization. As it was established earlier - normalization distorts frequency composition of earthquakes. The average value of horizontal components values is 432.24 cm/s^2 with standard deviation 247.08, which corresponds to 9-point earthquake. It should be noted that accelerogram 7.2 has a character loading. This effect was found in the analysis of instrumental records of the earthquake January 23, 2024 in Almaty. Figure 10 shows a sample of an artificial accelerogram.

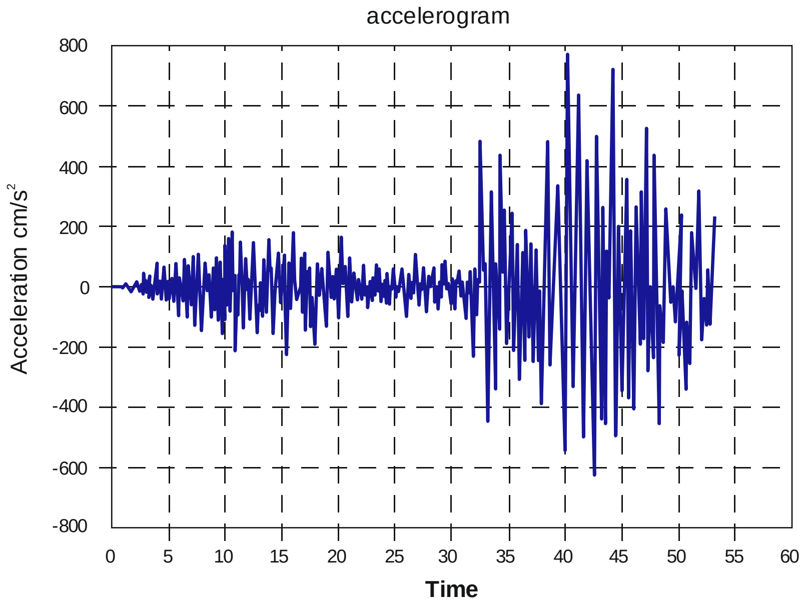

Figure 10. Artificial accelerogram

Table 2 presents the results of calculations on real accelerograms of building of 69 series on accelerograms from the sample (Table 3). Table 4 presents statistical estimates of the average value of maximum displacements (skewness). Note that the 5-story building of 69 series has a height h = 1500 cm. The limit value of the skewness limit [x] is usually taken as h/400. Hence, [x] = 3.75 cm. We have, [x] > 2.01. Consequently, the building of 69 series is earthquake-resistant, which coincides with the results of passportization, where this type of building is accepted as earthquake-resistant.

Table 2. Maximum displacement values

№	Accelerogram cipher	Maximum displacement values, cm
1.1	Aks1	3.08
1.2	Aks2	2.54
2.1	Aks24	0.59
2.2	Aks25	0.62
3.1	Aks7	1.64
3.2	Aks8	1.02
4.1	Aks135	0.35
4.2	Aks136	0.32
5.1	Aks190	4.36
5.2	Aks191	1.49
6.1	Aks180	3.92
6.2	Aks181	2.31
7.1	Aks201	2.58
7.2	Aks202	3.58

Table 3. Selection of three-component earthquake accelerograms for calculations of seismic isolation systems in the region of Almaty city

No.	Accelerogram cipher	Earthquake, year, focal parameters	Intensity, cm/s^2	Component
1	Two-component accelerogram	cm/s^2	digitization step - 0.00657	gain - 13.3333
1.1	Aks1	Gazley, 17/05/76. R=24, M=7.2	603.0	C-Y
1.2	Aks2	Gazley, 17/05/76. R=24, M=7.2	704.0	B-Z
2	Two-component accelerogram	cm/s^2	digitization step - 0.02	gain 1.0
2.1	Aks24	KERN COUNTY, 21/07/52 R= 41, M= 7.2	152.7	
2.2	Aks25	KERN COUNTY, 21/07/52 R= 41, M= 7.2	175.9	
3	Two-component accelerogram	cm/s^2	digitization step - 0.02	Gain 1.0
3.1	Aks7	EL-CENTRO, 18/05/40 R=31, M=6.5	341.7	S00E
3.2	Aks8	EL-CENTRO, 18/05/40 R=31, M=6.5	210.1	S90W
4	Two-component accelerogram	cm/s^2	digitization step - 0.02	Gain 1.0
4.1	Aks135	KERN COUNTY, 21/07/52 R= 89, M= 7.2	87.8	N42E
4.2	Aks136	KERN COUNTY, 21/07/52 R= 89, M= 7.2	128.6	S48E
5	Two-component accelerogram	cm/s^2	digitization step - 0.008	Gain 1.0
5.1	Aks190	BAYSORUN, 12/11/90 D= 35, H=20, M= 6.3	699.2	N-S
5.2	Aks191	BAYSORUN, 12/11/90 D= 35, H=20, M= 6.3	437.0	E-W
6	Two-component accelerogram	cm/s^2	digitization step - 0.025	Gain 1.0
6.1	Aks180	Loma PRIETA, 18/10/89. R=19, H=18, M=7.1.	627.0	
6.2	Aks181	Loma PRIETA, 18/10/89. R=19, H=18, M=7.1.	490.0	
7	Two-component accelerogram	cm/s^2	digitization step - 0.0064	Gain 1.0
7.1	Aks201	Artificial M=7.4	460.15	OX
7.2	Aks202	Artificial M=7.4	674.91	OY

Table 4. Statistical characteristics of maximum displacement values

Characterization	Magnitude
Average value, cm	2.01
Standard (standard deviation), cm	1.35
Coefficient of variation	0.67

3.5. Calculation of Reliability Values of the 464 Series Building

There are experimental data on the behavior of the 464 series building under vibrodynamic effects in Navoi city [17]. It was revealed that the building behaves as a significantly nonlinear single-mass system. Therefore, the dynamics of such a system is described by a nonlinear differential Equation:

$$m\ddot{x} + \mu\dot{x} + R(x) = -m\ddot{x}_0 \tag{3}$$

Figure 11 shows the deformation diagram of the 464-series building.

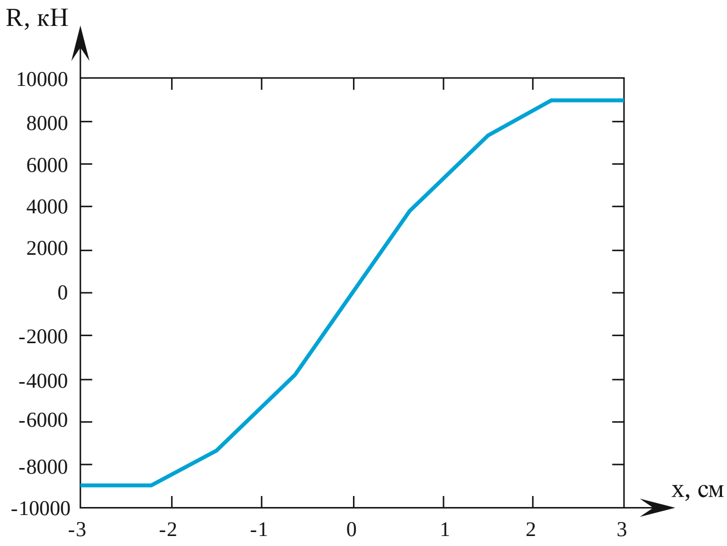

Figure 11. Deformation diagram of the 464 series building

The deformation diagram of the dynamic building model is assumed to be piecewise linear. Table 5 shows the parameters of the inflection points of the diagram.

Table 5. Parameters of the deformation diagram

Parameters	Values of inflection points of the building deformation diagram								
Movements, cm	-3	-2.2	-1.5	-0.64	0	0.64	1.5	2.2	3
Reaction, kN	-9000	-8960	-7360	-3840	0	3840	7360	8960	9000

The parameters μ=30.26 kN cek/cm, m= 16 kN cek2/cm are assumed in Equation 3.

The Monte Carlo method was used to determine the reliability W (probability of failure-free operation). The limit state is taken as the exceeding of the limit displacement of the building equal to [x]=h/400. Then, taking into account the height of the building [x]=3.75 cm.

The seismic impact is modeled by realizations of a nonstationary random process, which is obtained from a stationary one by multiplication by a fractional-rational function (by artificial accelerograms). The correlation function of the stationary random process has the following form:

$$K(\tau) = \sigma^2 e^{-\alpha\tau}\left(\cos\cos(\omega\tau) + \frac{\alpha}{\omega}\sin\sin(\omega\tau)\right) \tag{4}$$

where σ is the acceleration standard, α is the correlation parameter, ω is the carrier frequency of seismic impact. It is accepted α =2.41/cek, these parameters correspond to regional peculiarities of seismic impact for the city of Almaty.

A mathematical filtering method is used to generate artificial accelerograms. The average value of acceleration values at the base here is 402 cm/s^2, which corresponds to the intensity of seismic impact of 9 points. Equation 3 was integrated using the implicit Runge-Kutta method of MATLAB program package.

Tables 6 to 8 show the probabilistic characteristics of displacements (skewness) of a large-panel building of the 464 series obtained at different number of realizations of the random process (artificial accelerograms) used in the calculation

Table 6. Probabilistic characteristics of displacement values and reliability (500 realizations)

Parameters	Values
Reliability W	0.996
Average value, cm	1.97
Median, cm	1.90
Standard, cm	0.51
The third point (asymmetry)	0.78
The fourth point (excess)	1.06

Table 7. Probabilistic characteristics of displacement values and reliability (1000 realizations)

Parameters	Values
Reliability W	0.997
Average value, cm	2.0
Median, cm	1.94
Standard,cm	0.53
The third point (asymmetry)	0.84
Fourth moment.	0.99

Table 8. Probabilistic characteristics of displacement and reliability values (3000 realizations)

Parameters	Values
Reliability W	0.995
Average value, cm	1.97
Median, cm	1.91
Standard,cm	0.53
The third point (asymmetry)	0.83
Fourth moment.	0.98

The analysis of Tables 6 and 7 shows that further increase in the number of realizations is reasonable only for specifying the higher displacement moments. The average value of displacements does not change and is equal to 2 cm. The value of the median of displacements changes by 2%, and the standard changes by 5%.

Table 8 shows the results of calculations when using 3000 realizations of the random process (artificial accelerograms). The magnitude of reliability practically did not change; the mean values and the median of displacements did not change either. The values of asymmetry and excess have changed insignificantly. Consequently, Table 8 summarizes the reliable solutions to the problem.

Figure 12 shows the probability distribution function of displacements (skewness), as well as the minimum and maximum values of the 464 series large-panel building. The distribution function is obtained on the basis of the application of the MATLAB mathematical package. By applying this graph, it is possible to determine the displacement values with a given security.

Comparing Table 4 with Tables 6 to 8, we find that the average displacement values for the buildings of the 69 and 464 series coincide and are approximately equal to 2 cm. This is in spite of the fact that different models of dynamic systems and seismic impact were used for these buildings. This indicates the reliability of the calculations based on experimental data. Thus, the buildings of the 464 series are also earthquake resistant, taking into account the regional peculiarities of seismic impact for the city of Almaty.

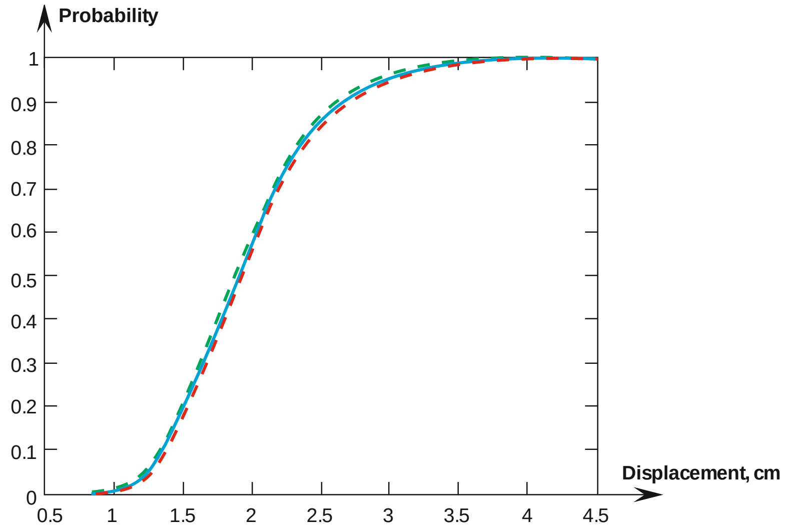

Figure 12. Displacement distribution function of the building under 9-point seismic impact

4. Discussion

As a hypothesis, we will consider the above results to be true and obtained when the accepted failure criterion is realized. Failure Q is an event consisting in the fact that in case of an earthquake of intensity 9 points the degree of damage to the object will be such that its further functioning will be excluded. Attribution of a building to the class of non-seismic resistant is performed by a group of experts who, based on previous experience and objective information, attribute it to the specified class. Let us assume that the conditional probabilities of failure at the specified values of acceleration are the same, i.e. earthquake-resistant buildings are such even at standard values of acceleration. The scheme with earthquakes with recurrence once in 475 years and once in 2475 years is realized. The service life of the building is assumed to be 50 years.

In Table 9, buildings with the first flexible or brick floor are categorized as the rest of the efficiency types, the failure probability of such buildings is significant. The last row of Table 2 shows the total failure probabilities for all large-panel buildings Q_{475}=0.0866 and Q_{2475}=0.0165. Then the total Q_{kpd}= Q_9 P_{2475} + Q_9 $P_{(475)}$. Then the probability of failure for the group of large-panel buildings of Almaty city will be equal to Q_{KPD}=0.1031. Then the value of total reliability for the group of large-panel residential buildings is as follows:

$$Wkpd = 1 - 0.0866 - 0.0165 = 0.8969 \tag{5}$$

The obtained value of general reliability Wkpd is an objective quantitative characteristic of the condition of a group of large-panel multi-story residential buildings in Almaty, taking into account the recurrence of seismic impact and division into series. Further actions can change the specified value of Wkpd.

Table 9. Characteristics of failure probability Q considering earthquake recurrence for large panel buildings

№	Design solution	Failure rate by type of large-panel buildings	Failure rates at 475 year repeatability	Failure rate at a repeatability of 2475 years
1	464-DS	0	0	0
2	464-AS	0	0	0
3	69	0	0	0
4	E147	0	0	0
5	158	0	0	0
6	Other types of efficiency	0.825	0.0866	0.0165
	Total		**0.0866**	**0.0165**

Note that the estimation of failure probability by building series is very convenient for reliability management. If we reinforce all large-panel buildings with the first flexible floor or brick floor - 33 buildings, in this case for all types of large-panel buildings, the probability of failure Q9=0. Then the reliability for all series of large-panel buildings will be equal to Wkpd=1. It should be noted that the failure probability can also be determined using other methods for determining failure probability and reliability [44, 45] developed by domestic and foreign specialists.

The results of this study should be compared with the qualitative and quantitative assessments of other specialists. It has been found that during strong earthquakes in Eastern European countries and the former Soviet Union, no seismically resistant buildings were destroyed. The catastrophic 1988 Spitak earthquake in Armenia, which claimed over 25,000 lives, also confirmed the high level of resilience of such buildings under severe seismic impact. There were no collapses of these buildings during the 9–10 intensity Gazli earthquake of 1976 either. It is worth noting that the Gazli area was not considered seismically hazardous, so large-panel and brick buildings were constructed without seismic reinforcements. However, unlike brick buildings, not a single large-panel house collapsed.

The widespread adoption of large-panel buildings was facilitated by experimental research conducted at scientific institutes in the former Soviet Union (Moscow, Almaty, Kyiv, Tashkent) and Eastern European countries. The consensus was unanimous—large-panel buildings are seismically resistant, and their construction is more economically viable compared to frame structures. The labor intensity of construction is 15–20% lower, the estimated cost is 13–40% lower, and steel consumption is significantly reduced. Once again, it should be emphasized that the high seismic resistance of large-panel buildings is determined by the strength of factory-made components, significant spatial rigidity, lower mass compared to brick buildings, friction forces in panel joints, energy dissipation capacity, and a high degree of static indeterminacy.

The results of this study have practical significance for Eastern European countries, the Balkan region (Croatia, Serbia, Bulgaria), as well as the former Soviet Union, where a large number of residential buildings have been constructed using panel structures. The passporting of over 2000 large-panel buildings has identified non-seismic-resistant (faulty) structural solutions in such buildings. Calculations based on refined seismic impact models have allowed for a more accurate assessment of the reliability of these buildings under intense seismic conditions, which may occur during earthquakes of up to magnitude 8.

It is interesting to estimate the damageability of large-panel buildings based on the results of the analysis of the consequences of strong earthquakes. In Tsipenyuk [12, 13], the damageability matrix of large-panel buildings obtained by analyzing the consequences of strong earthquakes is presented. Damageability of large-panel buildings in earthquakes can be characterized by the average value or mathematical expectation of the damage degree d(IJ) of a building of design intensity I with seismic impact of intensity J. The matrix was obtained on the basis of analyzing the consequences of 13 strong earthquakes (see Table 10).

Table 10. Damage matrix for large-panel buildings

Design seismicity of building I, points	Damage degree $d_{(IJ)}$ of the building under seismic impact with intensity J points		
	7 points	8 points	9 points
6	1.67	2.60	3.53
7	1.35	2.13	2.91
8	1.03	1.66	2.29
9	0.71	1.19	1.68

The damageability matrix proves to be a useful tool. Based on the design-level seismicity of buildings, it enables the estimation of expected damage during an earthquake of a specific intensity level, J. For the city of Almaty, the design seismic intensity for large-panel buildings is 9. Accordingly, the expected damage level (mathematical expectation) for such a building is d_{99} = 1.68. This corresponds approximately to the second degree of damage, which indicates the presence of minor (but clearly visible) cracks in individual structural elements and their connections. Additionally, similar cracks may appear in many non-load-bearing and self-supporting elements and their joints. In some cases, through-cracks may also develop in certain load-bearing and self-supporting components.

An empirically derived relationship exists between the degree of building damage and the associated restoration costs, as shown in Table 11. This scale was developed in 1983 by experts at the Research Institute of Organization and Management in Construction, affiliated with the V.V. Kuibyshev Moscow Institute of Civil Engineering (now MSCU).

Table 11. Amount of damage (cost of restoration work) depending on the degree of damage

Degree of damage	1	2	3	4	5
Amount of damage as a percentage of original cost	7.5	15	30	60	90

At the obtained value of the mathematical expectation of the degree of damage, the damage will be about 11% of the original value of the object.

In conclusion, it should be said that there are about a dozen of large-panel buildings on seismic-isolating kinematic foundations in the city of Almaty [16, 17]. In the future, other seismic isolating systems can be applied. These are kinematic-type seismic isolation systems [46] and systems based on the use of high-strength rubber blocks [47-49].

5. Conclusion

For the first time, comparisons of the response ditch parameters of two types of large-panel buildings have been made when the seismic impact is given in the form of a set of accelerograms or a random process. In both cases, the Monte Carlo scheme was used. The application of refined seismic models has not changed the assessment of earthquake resistance of large-panel buildings. They are still evaluated as the most earthquake-resistant residential buildings. Reliability assessments of two types of large-panel buildings are obtained on the basis of earlier experimental studies and application of the numerical Monte Carlo method. The seismic impact was modeled by real and artificial accelerograms. Estimates of reliability and seismic resistance correspond to the results of passportization.

Large-panel buildings with "first flexible floors" or brick walls on the first floor do not meet the requirements of current standards and are earthquake-prone. Buildings with these first floors require a detailed inspection with calculation and analytical assessment of the load-bearing capacity of structures and development of recommendations on the method of reinforcement. Large-panel residential buildings are not comfortable enough for living, and it is desirable to perform a set of works on their renovation. Acceptable methods for strengthening large-panel buildings with "soft first stories" or brick walls on the first floor include installing various seismic isolation systems beneath them. Traditional strengthening methods with the installation of rigidity diaphragms can also be used.

6. Declarations

6.1. Author Contributions

Conceptualization, V.L. and Y.A.; methodology, Y.A. and V.L.; validation, Y.A., V.A., Zh.M., and S.A.; formal analysis, Y.A.,V.L., Zh.M., and S.A.; investigation, Y.A., V.L., Zh.M., and S.A.; resources, Y.A.; data curation, Y.A. and S.A.; writing—original draft preparation, Y.A. and V.L.; writing—review and editing, Y.A. and Zh.M.; visualization, Y.A.,V.L., and S.A.; supervision, V.L.; funding acquisition, V.L. and Zh.M. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

6.3. Funding

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6.4. Conflicts of Interest

The authors declare no conflict of interest.

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